MODELLING THE SENSITIVITY OF CHANNEL ADJUSTMENTS IN DESTABILIZED SAND-BED RIVERS

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ABSTRACT

Comprehensive empirical data of the response of unstable streams over a range of environmental conditions are unavailable. In this study, as a substitute for empirical data, a physically based numerical model of channel evolution is used in a range of numerical simulation experiments designed to predict the sensitivity of channel response to changes in control variables. The scope of the study is limited by the scope of the numerical model which applies to straight, sand-bed streams with cohesive bank materials that have been destabilized by sediment starvation and evolve towards equilibrium through bed degradation followed by channel widening. Results are presented for stable and unstable channel conditions. Stable channel depths are most sensitive to channel discharge, though the critical threshold shear stress for the entrainment of cohesive bank materials and discharge are both significant in determining the width. The sediment load, channel gradient, bank material cohesion, size of failed bank material aggregates and the initial bank height have sensitivities an order of magnitude smaller than discharge for both width and depth. Variations in bed material characteristics within the sand-size range are found to have little impact on simulated stable channel morphology. For unstable channels, the relative dominance of parameter sensitivities is examined in the context of an empirical-conceptual model of channel evolution proposed by Thorne and Osman (1988), to highlight the relationships between parameter dominance, time, and the processes and forms characterizing individual stages of channel evolution. Rates of change with time of width and depth sensitivity parameters for five tested independent variables (discharge, sediment supply, channel gradient, bank material cohesion and bed material size) are found to vary as a function of time, such that different stages of channel evolution are characterized by variations in the relative dominance of tested variables. The results support the hypothesis proposed by Thorne and Osman (1988) that the critical bank height required to initiate mass-wasting and widening may be regarded as a geomorphic threshold.

KEY WORDS river channel evolution; sensitivity; numerical modelling; environmental change; river adjustment; sand-bed; geomorphic thresholds; destabilized

INTRODUCTION

Interest has been focused on establishing the sensitivity of channel adjustments to changes in independent variables (Graf, 1988; Schumm, 1991; Downs and Gregory, 1993). In turn, human-induced and natural environmental changes lead to changes in the values of independent fluvial system variables. Analyses of channel sensitivity try to answer the question, 'By how much will changes in independent variables influence the dependent variables that define the channel morphology?' The independent variables in question are the flow and sediment discharges imposed on a river channel by its watershed and the gradient of the valley in which the stream flows. In responding to disturbances in these independent variables, natural river channels may simultaneously adjust each of the dependent variables. These are the velocity distribution, flow resistance, width, depth, gradient, planform and boundary material characteristics (Hey, 1982; Simon, 1992).

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Various approaches have established quantitative relationships between dependent channel morphology variables and representative control variables, such as the 'channel-forming' discharge (e.g. Andrews, 1984; Hey and Thorne, 1986). However, these studies have tended to be empirically based, site-specific and restricted to steady-state, stable channel conditions. The few studies of channel evolution which are process-based and explicitly concerned with elucidating process–form interactions using temporally based data from natural, evolving channels, though valuable as case studies, are also site-specific in nature. These latter studies have formed the basis for conceptual models of channel adjustment in which various stages of channel evolution have been classified (e.g. Schumm *et al.*, 1984; Thorne and Osman, 1988; Simon, 1989, 1992). Each stage of channel evolution is characterized by distinct interactions between physical processes and morphological response. The variable nature of these process-form interactions as a function of time in the adjustment sequence also leads to shifts in the relative dominance and dependency of the fluvial system variables (Thorne and Osman, 1988; Simon, 1992), but such interactions are difficult to analyse. The question as to the sensitivity of channel adjustments in adjusting unstable channels has not yet been addressed within a mechanistic, process-based framework.

However, analyses of this type are subject to difficulties. The large number of boundary conditions that exist in natural river channels, together with the difficulty in obtaining temporally based data over the course of channel adjustment, mean that comprehensive empirical data, over a range of environmental boundary conditions, are not available. In these circumstances, an alternative approach (e.g. Murray and Paola, 1994) is to use a suitable numerical model to simulate channel adjustments to user-specified changes in environmental boundary conditions. Through such simulations, it is possible to address morphological relationships over a wider range of environmental boundary conditions than would otherwise be possible with empirical analyses alone. The key to the success of this approach is the selection of the numerical model. Particularly important is the requirement that the model is capable of simulating channel adjustments without artificially constraining adjustable variables. This is discussed in the next section.

The aim of this paper is to establish the relative dominance of channel morphology variables in controlling the sensitivity of channel adjustments in straight, sand-bed river channels with cohesive bank materials. A numerical model (Darby and Thorne, 1996), developed for analysis of rivers in this specific environmental category, is used to simulate channel responses to changes in independent variables. An overview of this model is provided, and the numerical simulation experiments and results obtained are discussed. Parametric sensitivity tests are used to rank channel sensitivities for steady-state stable channel and unstable channel conditions. For unstable channels, results are examined in the context of an empirical-conceptual model of channel evolution proposed by Thorne and Osman (1988), to highlight the relationships between parameter dominance, time, and the processes and forms characterizing individual stages of channel evolution.

NUMERICAL MODEL OF CHANNEL EVOLUTION

It is essential that model simulations replicate faithfully the behaviour of natural fluvial systems. However, the physical basis and predictive power of many existing alluvial channel models is limited because they often do not account for all the significant degrees of freedom involved in natural river channel adjustment. Specifically, most previous analyses (e.g. Thomas, 1982; Ikeda *et al.*, 1981; Parker *et al.*, 1983; Odgaard, 1989) assume a constant channel width through time. This is unrealistic, since channel response to a disturbance is frequently dominated by width adjustments (Thorne and Osman, 1988; Simon, 1992).

A physically based numerical model addressing this deficiency has recently been developed and tested. The ability of the model to stimulate channel widening as well as bed deformations was the reason for its selection. Full details of the development of the model, its limitations and scope, and assessment of its predictive ability are presented in detail in Darby and Thorne (1996) and Darby *et al.* (1996). So that this paper may stand alone, an overview is now presented.

Overview of the numerical model

The numerical model is quasi two-dimensional, accounting for temporal changes in channel depth, width, gradient, bed-material gradation and lateral depth-averaged velocity distribution. It solves each of the

deterministic equations of flow resistance, flow continuity, conservation of flow momentum, sediment transport, bank stability and conservation of sediment mass. The basis of the approach is to couple flow and sediment routing sub-models with bank erosion and mass-wasting sub-models to account for specific mechanisms of bank erosion, mass-wasting and channel widening.

The numerical algorithm of the model is illustrated in Figure 1. First, a method (Wark *et al.*, 1990) to solve a form of the flow momentum equations is used to predict the lateral distribution of depth-averaged flow

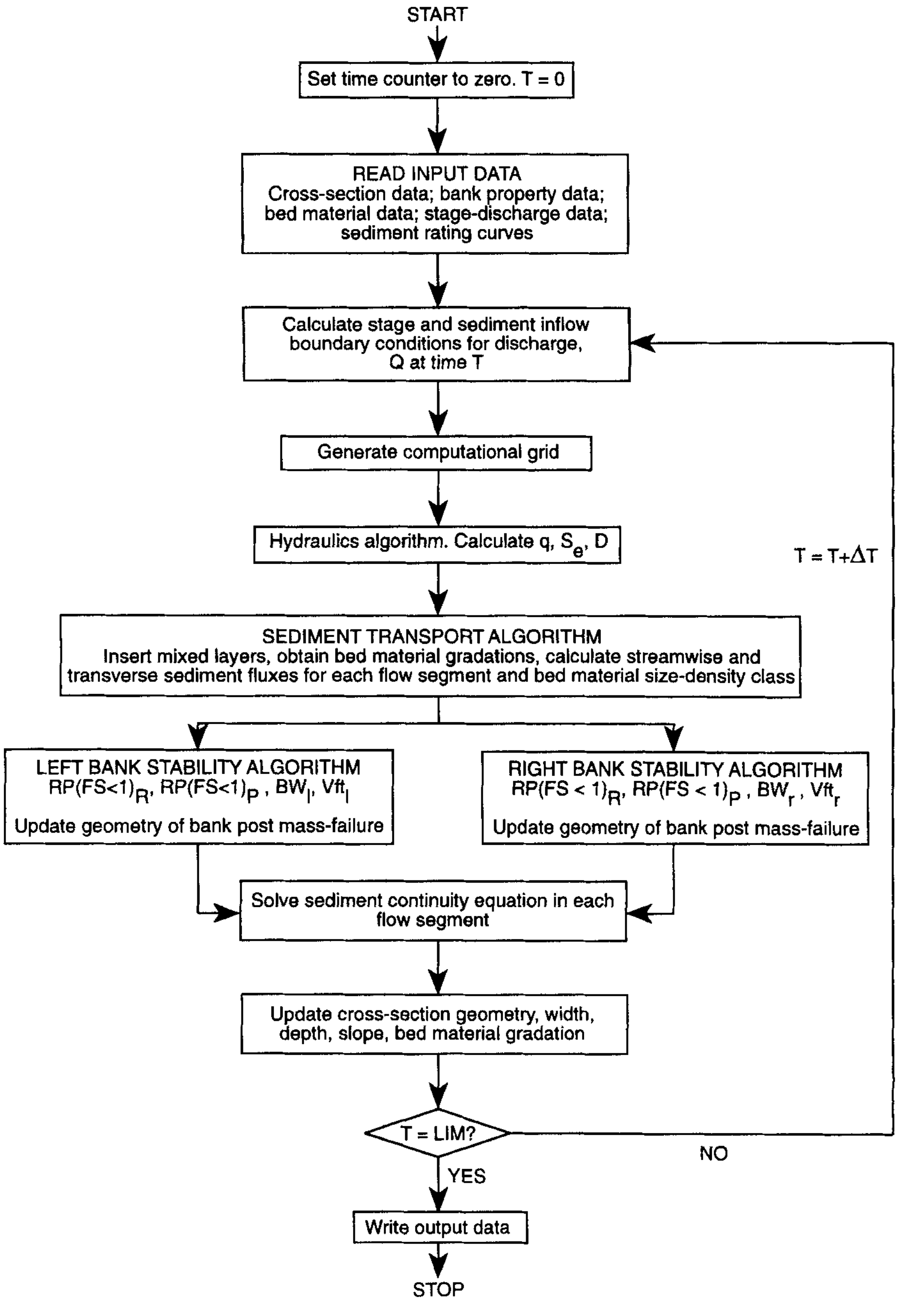

Figure 1. Algorithmic structure of Darby–Thorne numerical model (from Darby and Thorne, 1996)

velocity and boundary shear stress at each cross-section. Wark *et al.* simplified the flow momentum equations by assuming steady, uniform flow with no secondary currents. Lateral shear stress terms are included in the momentum equations in order to account for the influence of friction due to the presence of the channel banks, which significantly influences the flow in the near-bank zone. Water surface elevations required for these computations are provided by applying the method in conjunction with a one-dimensional, gradually varied flow routing method solved using the standard step method. The method requires a stage–discharge relationship to be provided as the downstream boundary condition. The method is capable of simulating flows in channels with longitudinally non-uniform bathymetry, but channels with islands or emergent mid-channel bars cannot be simulated. The impact of boundary materials on flow resistance is accounted for using an empirical roughness law (Strickler, 1923). Secondary and over-bank flows are excluded from the analysis, which at present is intended for straight channels only.

Streamwise sediment transport fluxes are calculated using the Engelund and Hansen (1967) sediment transport relationship, while transverse fluxes are calculated using the methods presented by Parker (1978). The sediment transport equations used in the model are valid for sand-bed materials; gravel-bed materials are excluded from the analysis at present.

For the purposes of the sediment routing computations only, each cross-section is divided laterally into three segments. Each near-bank segment extends laterally a distance of two bank heights towards the centre of the channel. Predictions of changes in bed elevation, which determine changes in channel depth and gradient, are obtained in each of these segments via numerical solution of the sediment continuity equation using a centred finite-difference scheme. Sediment inflow at the upstream boundary is the required boundary condition. The use of three flow segments is an advantage over strictly one-dimensional numerical models, since bank stability is controlled by changes in bed elevation close to the banks (Andrews, 1982). The quasi-two-dimensional approach allows better resolution of changes in bed elevations in the near-bank zones to be obtained.

Fluvial shear erosion of the cohesive bank materials is estimated using an empirically derived excess shear stress method (Arulanandan *et al.*, 1980). Estimates of lateral erosion, together with the predictions of changes in bed elevation in the near-bank zones, allow variation in bank geometry to be simulated through time. Geotechnical bank stability analyses for cohesive bank materials, based on those developed by Osman and Thorne (1988), are then used to check the stability of the banks, and to determine the geometry of failure if instability is predicted. Channel widening is simulated by updating the cross-sectional geometry coordinates according to the geometries of predicted mass-failures. The longitudinal extent of mass-failures within modelled reaches is estimated by equating the fraction of bank length that fails in any time step to the probability of failure. Estimates of fluvial erosion of bank material and mass-wasting computations are obtained independently for each bank, so that asymmetrical channels can be simulated.

In the time steps after mass-failure, failed bank material becomes one of bed material, bed material load, wash load or bank material, based on its physical properties and the hydraulic properties of the near-bank flow. Immediately after failure, bank materials are distributed evenly over each near-bank sediment routing segment. Transport of the bed and bank material mixture is accounted for deterministically through use of a mixed-layer theory (Rahuel *et al.*, 1989) which routes sediment by grain sizes and densities. This approach allows temporal changes in the bed material gradation to be simulated and accounted for in subsequent time steps.

Assessment of the ability of the new model to predict channel adjustment through time has been based on comparison between observed and predicted channel conditions (top-bank widths and channel depths) between 1969 and 1993 on a reach of the South Fork, Forked Deer River, Western Tennessee. In addition, model-generated and empirically derived hydraulic geometry equations relating channel width and discharge have been compared (Darby *et al.*, 1996).

Figure 2 illustrates simulated and observed channel widths and depths at Chestnut Bluff and Crossroads, the two study sites for which observations were available throughout the period 1969–1993. Quantitative comparisons between observed and predicted widths, depths, and channel widening and deepening rates are expressed by the mean of the discrepancy ratio (Me), and the mean absolute deviation of the discrepancy ratio (Ad) (Table I). Perfect agreement between observed and predicted data is indicated by $Me = 1$ and

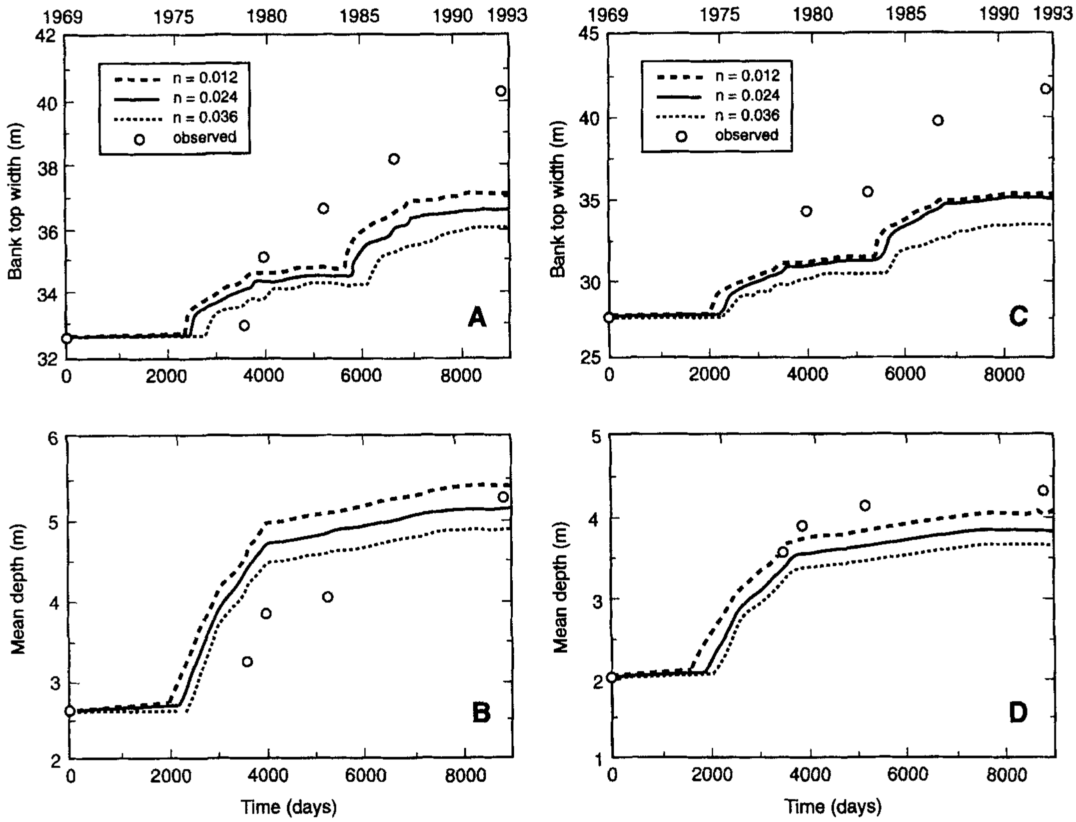

Figure 2. Comparisons of simulated and observed trends of (A) channel width at Chestnut Bluff, (B) channel depth at Chestnut Bluff, (C) channel width at Crossroads, (D) channel depth at Crossroads for a range of Manning n values (from Darby *et al.*, 1996)

Table I. Summary of calculated mean discrepancy ratio and absolute deviation of discrepancy ratio for channel morphology variables (from Darby *et al.*, 1996)

	Chestnut Bluff		Crossroads		Overall	
	Me*	Ad†	Me*	Ad†	Me*	Ad†
Width, B (m)	0·962	1·086	0·887	1·067	0·925	1·105
Depth D (m)	1·176	1·258	0·990	1·284	1·084	1·340
Widening rate $\partial B/\partial t$ (m day^{-1})	0·275	0·305	0·370	0·412	0·323	0·358
Deepening rate $\partial D/\partial t$ (m day^{-1})	0·932	0·393	0·827	0·766	0·880	0·579

$$* Me = \frac{1}{nd}\sum_{i=1}^{nd}\left(\frac{X_p}{X_0}\right)$$

$$\dagger Ad = \frac{1}{nd}\sum_{i=1}^{nd}\left|\left(\frac{X_p}{X_0} - Me\right)\right|$$

where X = parameter value, nd = number of data points, and subscripts p and o are predicted and observed values, respectively

$Ad = 0$. Table I shows that simulated channel widths and depths are, on average within ±10 per cent of the corresponding observed values. However, this provides a misleading impression of the predictive ability of the model, as total observed changes in width and depth are comparable to this discrepancy. In these circumstances a more appropriate criterion of model performance is to compare simulated and observed widening and deepening rates. On average, simulated deepening rates are within 12 per cent of observed values, but widening rates are severely underpredicted, by a factor of about three.

Assessment of the ability of the model to predict stable channel forms is based on simulation experiments reported by Darby *et al.* (1996), in which the model was used to replicate the form of empirically derived hydraulic geometry equations which relate width to channel-forming discharge, Q. Table II compares model-generated hydraulic geometry equations obtained for a range (2–40 kPa) of bank material cohesion values, with the empirically derived Simons and Albertson (1963) hydraulic geometry equation for sand-bed streams with cohesive bank materials. It can be seen that, while the predicted and empirically derived intercepts in these equations are quite distinct, there is close agreement between model-generated and empirically derived exponents on the discharge.

Limitations of the model and scope of simulations

Conclusions drawn from the results of the numerical simulation experiments reported below are valid only within the limits of the applicability of the model, and the scope of the study. The chosen model is applicable to straight, sand-bed channels with cohesive bank materials. Flows are assumed to be sub-critical, steady and uniform within any computational time step. Unsteady flows may be modelled through the use of a stepped hydrograph. Secondary and over-bank flows are neglected. The model is applicable to non-layered river banks which either remain stable with respect to mass failure, or fail along approximately planar or circular failure surfaces which pass through the toe of the bank. The effects of vegetation, pore water pressure and hydrostatic confining pressure on bank stability are not accounted for.

The scope of the study is defined by the baseline values of the input data and the range over which tested parameters were varied in the course of the numerical experiments (Table III). The baseline numerical experiment was designed to simulate a straight, sand-bed, cohesive-bank channel destabilized by reduction in sediment supply, in which channel response was characterized by bed degradation followed by channel widening.

It is recognized that these limitations apparently contradict one objective of the modelling analysis, that is to analyse channel sensitivity over a range of environments. However, if the model were applied blindly in a range of environments for which it is not developed, the results obtained would simply not be valid. The Darby–Thorne model was chosen because, unlike most previous models, it accounts for specific mechanisms of bank erosion and channel widening which are significant in many unstable channels. Other numerical models are available which are valid in a wider range of environments. But these models all assume a constant fixed width through time and as such are severely limited in validity. In any case, sand-bed channels with cohesive bank materials are common in many parts of the world. A wide range of discharges and sediment loads flow through these channels, which are located in valleys with a range of gradients. The channels themselves have bank materials with a range of physical properties. These factors provide sufficient variation that a modelling study of this category of channels is justified.

Table II. Model-generated and empirically derived regime width equations (from Darby *et al.*, 1996)

Source	Regime width equation
Simons and Albertson (1963)	$B = 4{\cdot}842\,Q^{0{\cdot}493}$
Model simulation ($c = 40$ kPa)	$B = 5{\cdot}439\,Q^{0{\cdot}503}$
Model simulation ($c = 10$ kPa)	$B = 5{\cdot}411\,Q^{0{\cdot}504}$
Model simulation ($c = 2$ kPa)	$B = 5{\cdot}213\,Q^{0{\cdot}516}$

Table III. Tested control variables, baseline data set and variable ranges used in sensitivity analyses

Variable description	Symbol	Baseline value	Simulated range
Discharge	Q	100 $m^3 s^{-1}$	10–1000 $m^3 s^{-1}$
Upstream sediment inflow as percentage of transport capacity	Q_S	0·5	0–2·0
Downstream boundary stage as percentage of bank height	h	0·95	0·1–0·95
Width–depth ratio	B/D	10	Not varied
Channel gradient	S	0·001	0·0001–0·001
Bank height	H	3·60 m	2·70–3·60 m
Bank angle	α	60 degrees	Not varied
Manning n	n	0·025	0·015–0·035
Bed material diameter	d_{50}	1 mm	0·025–2·0 mm
Bed material specific gravity	SG	2·65	2·20–3·00
Critical shear stress for bank material entrainment	τ_c	99 dynes cm^{-2}	14·6–99·0 dynes cm^{-2}
Bank material cohesion	c	10·0 kPa	2–40 kPa
Bank material friction angle	ϕ	32·5 degrees	Not varied
Bank material unit weight	γ	19·0 kN m^{-3}	Not varied
Tension crack depth as fraction of bank height	K	0·0	0–0·5
Bank material sand fraction	SAND	0·2	0–0·4
Bank material sand size	d_{sand}	1 mm	0·25–2 mm
Size of bank material aggregates after mass-failure	d_{bank}	10 mm	1·25–80 mm
Bank material specific gravity	SG_{bank}	1·79	1·10–2·00
Bed material porosity	λ	0·40	0·30–0·50
Coulomb friction coefficient	μ	0·65	0·45–0·85

NUMERICAL SIMULATION EXPERIMENTS

Definition of sensitivity parameters

Sensitivity parameters defined here are the width sensitivity parameter $Sr(B)$ and depth sensitivity parameter $Sr(D)$. The sensitivity parameters represent measures of how changes in the magnitude of independent variables impact the dependent variable of interest. Sensitivity functions have a mathematical basis derived from a Taylor series expansion (McCuen, 1973). Following McCuen (1973) in assuming that the linear terms of the Taylor expansion are dominant, the relative sensitivity parameter Sr is here defined using:

$$Sr = \frac{\partial F_o}{\partial F_i}\frac{F_{ib}}{F_{ob}} \tag{1}$$

where F represents the variable subjected to sensitivity analysis and the subscripts o, i and b represent output, input and baseline values, respectively. Equation 1 is evaluated by perturbing the control or input variable, F_i, in uniform amounts away from its baseline value F_{ib}, according to a range that is typical for the case of interest. For each perturbation, finite-difference approximations are used to evaluate Equation 1. These are given by:

$$\frac{\partial F_o}{\partial F_i} \approx \frac{\Delta F_o}{\Delta F_i} \tag{2}$$

where

$$\Delta F_o = F_o - F_{ob} \tag{3}$$

$$\Delta F_i = F_i - F_{ib} \tag{4}$$

Ranking the magnitudes of the relative sensitivity parameters provides a simple means of discerning the relative dominance of each control variable on the various aspects of channel adjustment.

Approach

A programme of numerical simulation experiments was devised to calculate the sensitivity parameters defined above, for each of the controlling variables listed in Table III. In each experiment the analysed control variable was varied over a prescribed range (Table III), while holding the initial values of other model input variables constant at the 'baseline' values. For a valid sensitivity analysis, it is essential that the baseline values and input ranges of the tested variables are realistic. Often, such values are chosen based on real river channel data. This approach is not adopted here as the aim is to produce non-site-specific results and it is also not clear how to define 'baseline' values of discharge and sediment load for natural channels with temporally variable water and sediment discharges. Here, realistic values of the input variable ranges have been specified (albeit arbitrarily in some cases) to represent the category of channel under investigation, with baseline values where possible set as the median of the range (Table III). Test simulations indicate that the results are not significantly affected by the precise magnitudes of the baseline values.

It is stressed that the baseline values of most of the tested variables shown in Table III represent initial conditions only. Adjustable morphological variables, for example bank height, bank angle and Manning's *n*, were allowed to vary from these initial values during model simulations and were not held constant or otherwise constrained. Output data obtained from the simulations were used to calculate the sensitivity parameters, using Equations 1 to 4.

Some variables listed in Table III were not subjected to parametric sensitivity analysis. In preliminary simulations, bank material friction angle and bank material unit weight were found to partially control the stability of the banks, but results are similar to those obtained for cohesion. For simplicity, the influence of geotechnical characteristics is presented here using the cohesion exclusively. For the same reason, the effects of bank angle on bank stability were excluded as these are considered in the initial bank height tests. Although probably significant, analysis of width-to-depth ratio was excluded from this study, which is concerned with the impacts of change in external fluvial system variables.

Hypothetical input data were selected to simulate a moderately steep, straight, uniform channel with sand-bed and cohesive bank materials (Table III). The baseline data were selected to represent a channel out of equilibrium with the constraints of the imposed discharge, sediment load, boundary material properties and specified initial channel morphology, so that the channel response was to initially degrade and destabilize the banks, resulting in a channel adjustment sequence involving deepening followed by widening until a new, stable form was attained.

In each simulation, upstream boundary sediment loads (Q_s) were prescribed as fractions of the transport capacity at the first (upstream) model cross-section (Figure 3), to facilitate analysis of the impact of changing the sediment load in generating aggradational ($Q_s > 1$) or degradational ($Q_s < 1$) environments. This fraction was maintained at a constant value throughout model simulations. The magnitude of the imposed sediment load was, therefore, allowed to vary as a function of predicted transport capacity. In all simulations, bed material was initially sand with a uniform diameter of 1 mm. However, bed material size was allowed to adjust in some simulation in which inputs of distinct sand-sized fractions of entrained bank material occurred. In each simulation, the discharge was specified as constant throughout.

Simulations were run for real time periods of 300 days. In all the numerical experiments the model channel adjusted to a stable state within this period. The model channel was designed to be straight and initially uniform in geometry (same channel gradient and cross-section shape at each model cross-section) and bed and bank material characteristics. Numerical cross-sectional geometry data for each of the model cross-sections were calculated using the prescribed values of bank height (equal to bankfull depth), bank angle and width–depth ratios, together with the assumption of an initially trapezoidal cross-section shape. Model output data used to calculate the sensitivity parameters were obtained at two locations in the hypothetical model channel, at 'upstream' and 'downstream' cross-section sites (Figure 3).

Four simulations for each control variable were performed, with two values of the input variable set above the chosen baseline value and two below it, in addition to the baseline run. Consistent results for calculated

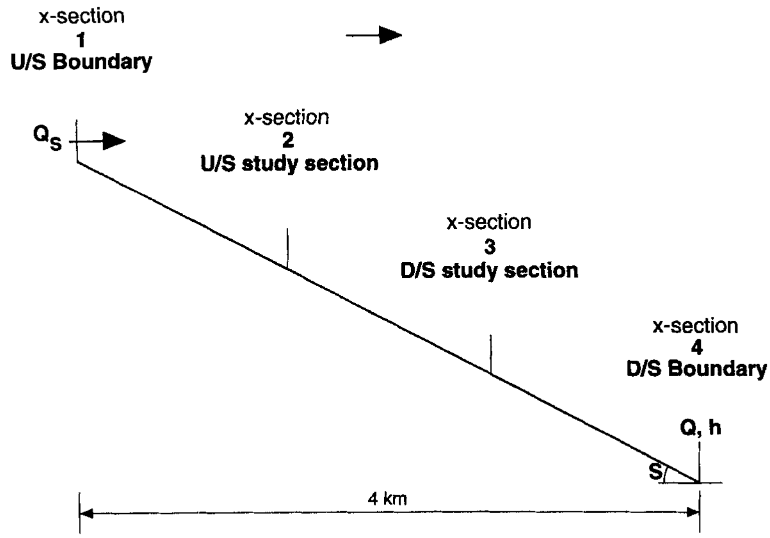

Figure 3. Diagram of initial characteristics of simulated channel and relative locations of study cross-sections

sensitivity parameters were obtained over the entire range of all tested variables. Calculated sensitivity parameters discussed below are the numerical mean of the four predicted sensitivity parameters obtained in these simulations.

RESULTS AND ANALYSIS

The relative dominance of tested variables was estimated by ranking model-generated sensitivity parameters. The results are presented in two sub-sections. First, the relative dominance of each parameter is assessed in terms of its impact upon simulated stable channel widths and depths by determining sensitivity parameters based on the (stable) morphological values obtained at the end of the simulations. Second, temporal aspects are addressed by quantifying the sensitivities of selected parameters during simulated channel adjustment. The latter results are examined in the context of an empirical-conceptual model of channel evolution proposed by Thorne and Osman (1988), to highlight the relationships between parameter dominance, time, and the processes and forms characterizing the stages of channel evolution.

In all simulations, temporal trends of adjustment of width and depth were qualitatively similar at both the upstream and downstream sites, though quantitative differences in response at the two locations led to systematic variation in the magnitudes of model-generated sensitivity parameters as a function of location in the modelled reach. Physically, these differences arose because the onset of widening is delayed at the downstream location, due to the extra time taken for bed degradation to migrate to downstream sections from the upstream disturbance. Additionally, widening rates are lower at downstream sections because additional sediment is supplied to these reaches from upstream bed degradation and bank failures. Relative rankings of sensitivity parameters are, therefore, presented here both by location in the hypothetical channel (Figures 4A and 4B) and in terms of an average value, termed the 'mean of location', which is the mean of the upstream and downstream sensitivity parameters (Figures 4C and 4D). No physical significance is placed on the 'mean of location' results, they are simply intended to clarify the discussion. This is justified because the relative rankings of the model-generated sensitivity parameters are, unlike the sensitivity parameter magnitudes, mostly independent of location within the simulated reach.

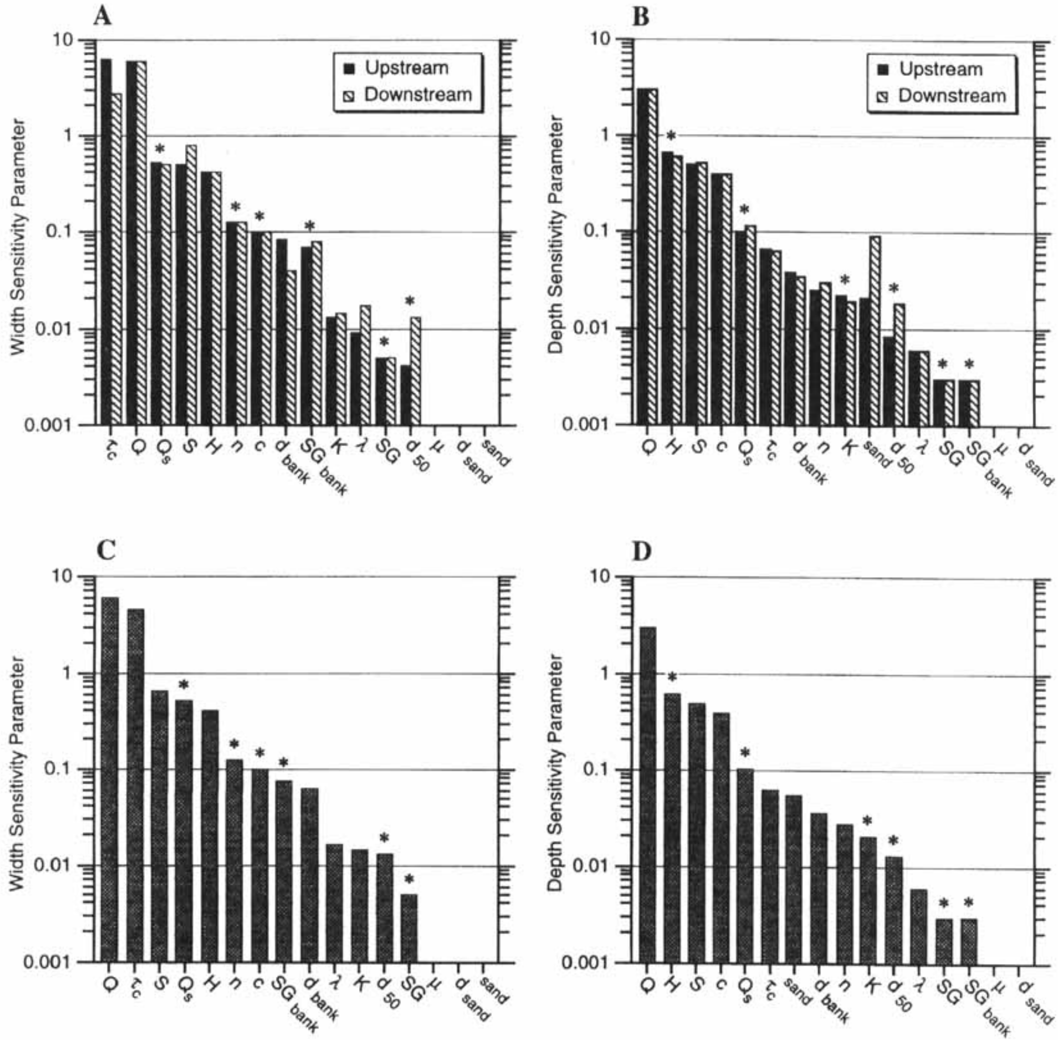

Figure 4. Absolute values of stable channel relative sensitivity parameters for tested variables for (A) channel width (upstream and downstream locations), (B) channel depth (upstream and downstream locations), (C) channel width (mean of locations), (D) channel depth (mean of locations). An asterisk indicates negative values

Relative dominance of variables controlling stable channel geometry

Figure 4 indicates that the most sensitive variables in determining overall changes in stable channel width are the discharge (Q) and the critical threshold for entrainment of the bank material (τ_c), and discharge alone in the case of stable channel depth. These variables have sensitivity parameters approximately an order of magnitude higher than all other tested variables, independent of location in the simulated reach (Figure 4). These results are only partly consistent with the traditional use of bivariate relationships in hydraulic geometry analyses, in which various channel morphology variables are related to a 'channel-forming' discharge alone.

In light of the predicted importance of the parameter τ_c, a particular question arises concerning the sensitivity of channel width to the discharge and bank material characteristics such as the bank material cohesion (c), bank height (H), tension crack index (K), as well as the resistance of the bank material to fluvial erosion (τ_c). Calculated sensitivity parameters for stable widths and depths for each of these variables

are at least an order of magnitude smaller than the corresponding sensitivity parameters for discharge, with the exception of τ_c for width, generally confirming that discharge is indeed the dominant variable. However, model output is also highly sensitive to τ_c, a result obtained independently by Borah and Dashputre (1994).

The difference in the rankings of channel *depth* sensitivity parameters for discharge and bank material cohesion (first and fourth) is much less than the difference in the channel *width* sensitivity parameters for these variables (first and seventh). Therefore, although discharge is the dominant variable for both width and depth, bank material cohesion is relatively more important in establishing *depth* than in establishing *width*, despite empirical analyses which have emphasized the role of bank material shear strength on the stable channel width (Charlton *et al.*, 1978; Andrews, 1984; Hey and Thorne, 1986). Intuitively also this is a surprising result, as bank properties should exert a direct control on width adjustment.

Resolution of this apparent paradox lies in recognition of the role that bank material characteristics play in controlling both the channel depth and width, but at different times in the channel adjustment sequence. For example, bank material cohesion partially determines the factor of safety of the banks and the critical geometry required to initiate mass failure and rapid widening. In these simulations depth freely adjusts prior to the onset of bank instability, while the width is constrained by the stability of the banks. Once bed degradation causes the critical bank height for generating instability with respect to mass failure to be reached, bank retreat and widening is initiated, sediment is supplied to the channel from bank failures, boundary shear is reduced as the channel widens and the rate of degradation slows and/or ceases. This limits further degradation, so the geotechnical characteristics control depth adjustment as well as width adjustment. Values of width and depth sensitivity parameters for bank material cohesion before and after the shift in morphological response are examined further in the next section.

A number of other variables have sensitivity parameters approximately one order of magnitude smaller than the discharge (Figure 4). Although not as dominant as discharge, these variables influence stable channel widths and depths within the constraints set by the flow regime determined by the catchment hydrology.

The sediment load supplied from the upstream boundary of the model (Q_s) is, as a major independent variable, expected to have a significant influence on channel geometry. This is only partially supported by the results. For stable channel width (Figure 4C), the sediment supply ranks as the fourth most dominant parameter—below discharge, the critical entrainment threshold of the bank material, and channel gradient—but ranks above hydraulic roughness and the various bank material characteristics. For stable channel depth (Figure 4D), sediment supply ranks fifth overall, with discharge, initial bank height, channel gradient and bank cohesion all above this parameter, though the latter three have sensitivity parameters with similar orders of magnitude. The mean sensitivity of overall change in channel width to sediment supply ($Sr(B) = -0{\cdot}506$) is approximately five times the sensitivity of channel depth ($Sr(D) = -0{\cdot}104$). This is an unexpected result, as Q_s is expected to directly impact bed elevation changes through its influence on aggradation and degradation. Impacts on width are less direct, width response being determined by bank stability, which in turn is governed by bed elevation changes. Explanation of this result again depends on the temporal distribution of depth and width adjustments. Depth sensitivity parameters in Figures 4B and 4D reflect only overall predicted changes in channel depth. Channel response in these simulations is actually characterized by an intial degradational phase, followed by widening and then, in response to the additional sediments so supplied, a reduction of depth so that the final depth happens, in this case, to be closer to its initial value than would otherwise be expected. Q_s has a more significant impact on depth adjustment in early stages of channel evolution than it does for the stable channel value of channel depth. This is demonstrated in the next section, when temporal changes are considered in detail.

The intial channel gradient (S), which in these simulations is equal to the valley gradient, is another variable expected to have a significant impact on channel morphology, through its influence on the available stream power. Calculated sensitivity parameters (Figure 4) indicate that the channel gradient is the third most important variable for changes in both stable channel depth ($Sr(D) = 0{\cdot}500$) and stable width ($Sr(B) = 0{\cdot}639$). For depth (Figure 4D), channel gradient ranks below only discharge and intial bank height. For width (Figure 4C), channel gradient ranks below discharge and the critical threshold for erosion of the bank material.

The size of the bank material aggregates deposited after mass failure (d_{bank}) is a 'third order' variable for the sensitivity parameters corresponding to overall changes in both width and depth. The magnitudes of the calculated sensitivity parameters ($Sr(B) = 0.061$; $Sr(D) = 0.036$) are similar, indicating that this parameter influences width and depth changes approximately equally, over the range of values tested here. This variable ranks ninth and eighth out of the 16 variables tested, for channel width and depth, respectively (Figure 4). Physically, the size of failed bank material aggregates partially controls their transport rate following mass-failure of the banks. The specific gravity of these aggregates (SB_{bank}) also controls this process. Not surprisingly, then, SG_{bank} is also a mid-ranking parameter (ranking eighth for width), though its significance with respect to other variables is lower for channel depth (ranking 14th). Therefore, physical properties of failed bank materials appear at best to have only moderate significance with respect to stable channel morphology.

Hydraulic roughness (Manning's n coefficient) is found to be moderately significant with respect to the other fluvial system variables. It is ranked sixth of width sensitivity parameters ($Sr(B) = -0.122$) and ninth for depth ($Sr(D) = 0.054$). These values are one and two orders of magnitude lower than the most dominant variables for width and depth, respectively (Figure 4). The calculated values indicate that channel width is more sensitive to changes in hydraulic roughness than is channel depth, which is surprising as the hydraulic roughness directly affects flow velocities and sediment transport processes, which in turn would be expected to primarily impact bed, rather than bank, processes. One possibility is that changes in roughness may tend to have a relatively greater impact on the sediment transport dynamics in the near-bank zone, which is subject to both bed and bank friction effects. Impacts felt in this zone would tend to influence bank processes more than processes acting across the full width of the bed.

Bed material property variables (specific gravity, median diameter, Coulomb friction coefficient and porosity) are amongst the lowest ranked fluvial system variables for both width and depth (Figure 4). Indeed, the values of the calculated sensitivity parameters are as low as to suggest that they have a negligible effect on the establishment of stable channel cross-section in these simulations. This result is related to the use of a hypothetical sand-bed channel with uniformly graded materials. Variations of bed material size within the sand-size range are not particularly large and increased sensitivity may have been predicted if a wider range of bed materials had been used, by including gravel-bed materials, for example. This is not possible with the present model, but the inclusion of gravel-bed materials in future versions of the code is planned. It appears that the sand-bed material characteristics are of negligible significance compared to discharge, slope, sediment load and bank material characteristics in establishing the stable channel geometry.

Shifting dominance of variables during channel adjustment

The preceding results provide information only about the mean relative dominance of fluvial system variables on stable channel morphologies; they do not provide information about how the dominance of these variables shifts during channel adjustment. To examine this, relative sensitivity parameters for channel width and depth for five independent fluvial system variables were calculated at each time step of the model simulation. From plots of the sensitivity parameters versus time, the relative dominance of the control variables at any stage in the simulation was estimated. Variables selected for analysis were the discharge (Q), sediment load at the upstream boundary (Q_s), channel gradient (S), bank material cohesion (c), and median bed material diameter (d_{50}). These variables represent the primary independent variables of natural fluvial systems.

Temporal plots of absolute values of the mean width and depth sensitivity parameters so obtained for the selected fluvial system variables are shown in Figure 5. Notice that the sensitivity parameters are plotted on a logarithmic axis. Calculated sensitivity parameters equal to zero are actually assigned values of 0·001 on these plots. Also shown on this diagram are schematic illustrations of the various stages of an empirical-conceptual model of channel evolution (Thorne and Osman, 1988). Comparisons of the relative dominance of fluvial system variables in terms of the influence they have on channel depth and width at the various stages of adjustment are thus placed within the context of the shifting process–form interactions identified by Thorne and Osman (1988) in their model.

Stage 1 of the channel evolution model represents the initial condition of the channel (Figure 5C). Each of the variables on Figures 5A and 5B are predicted to have sensitivity parameters equal to zero (shown as 0·001

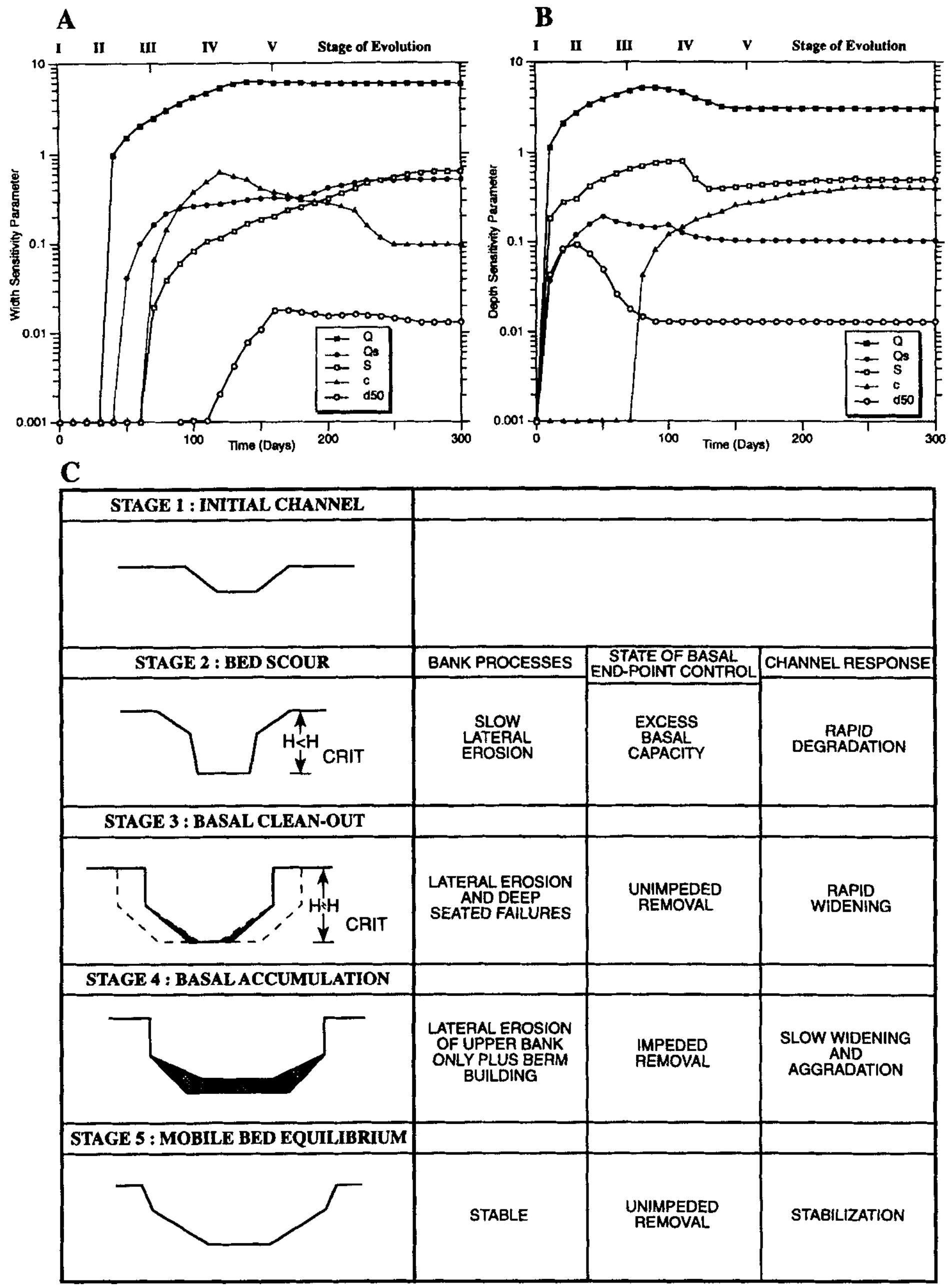

Figure 5. Simulated trends of absolute values of mean relative sensitivity parameters as a function of time and stages of Thorne and Osman (1988) conceptual channel evolution model for (A) channel width and (B) channel depth. (C) Schematic illustration of stages of Thorne and Osman (1988) conceptual model

on these plots) for both depth and width adjustment at this initial condition. Once the channel adjustment sequence is initiated (the simulation started), the channel is in Stage 2 of the evolution sequence (Figure 5C). In this phase, bank heights are less than the critical bank height required to generate mass-failure and widening. Sediment transport exceeds sediment supplied from the upstream boundary of the reach and the bed degrades. Stage 2 is terminated by the onset of channel widening, as the channel eventually deepens

to produce over-heightened and over-steepened banks that are unstable with respect to mass-failure. In these simulations, Stage 2 lasts until approximately day 70 of the simulation, though the precise duration is dependent on the values of the control variables.

During Stage 2, none of the tested variables have an impact on the width sensitivity parameter ($Sr(B) = 0{\cdot}001$ for all variables, Figure 5A) because at this time the channel is degrading, the banks are stable and there is no channel widening. The relative dominance of each of the tested variables with respect to channel depth varies during Stage 2 (Figure 5B). For discharge and channel gradient, depth sensitivity parameters rise non-linearly throughout Stage 2 of channel adjustment. The rate of change of depth sensitivity parameter with time decreases with time for these two variables. For the sediment load and bed material size, depth sensitivity parameters have similar initial trends, but reach maxima for the simulation and then decrease as Stage 2 progresses. Bank material cohesion has no impact on deepening during Stage 2, as bank processes are inoperative at this time. Throughout Stage 2, discharge is the dominant variable by at least an order of magnitude over the other tested parameters. Below the discharge, channel gradient is more significant than either sediment load, median particle diameter or bank material cohesion. The varying rates of change of the depth sensitivity parameters with time for these variables are such that the relative dominance of discharge over channel gradient is approximately constant throughout this stage. On the other hand, once the depth sensitivity parameters for sediment load and bed material size attain their maximum values, the sensitivity parameters for discharge and channel gradient continue to increase, so that their relative dominance over sediment load and median bed material particle size increases as Stage 2 progresses (Figure 5B). This is the reason for the relatively low ranking of the stable channel depth sensitivity parameter for sediment load obtained in the previous section.

Stage 3 represents the point at which a major discontinuity occurs in channel evolution. Immediately prior to this time, depth adjustment is dominant and mass-wasting processes are inoperative. Immediately following the onset of critical conditions for bank instability, widening commences, so that both bed and bank processes are active (Figure 5C). This shift in the dominant morphological response of the channel is reflected in the simulated results (Figures 5A and 5B) during Stages 3 and 4, when widening is active. Taking day 70 as the time of the simulation at which the channel is at Stage 3, Figure 5A shows that at this point there are rapid increases in the width sensitivity parameters for discharge, sediment load, cohesion and channel gradient, though the size of the bed material continues to have a negligible impact on channel widening and only becomes non-zero after day 100, well into Stage 4. The width sensitivity parameters for these variables vary at non-linear rates throughout Stages 3 and 4, leading to shifts in the relative dominance of the tested variables with respect to widening through Stages 3 and 4. The discharge width sensitivity parameter is at least an order of magnitude higher than the other tested variables, throughout Stages 3 and 4. The bed material size is the least dominant variable with respect to width throughout Stages 3 and 4, with a width sensitivity parameter approximately an order of magnitude lower than the closest variable.

More complex relationships characterize the relative dominance with respect to width of the sediment load, channel gradient and bank material cohesion during Stages 3 and 4. Just after the onset of widening (Stage 3), the width sensitivity parameter for bank material cohesion increases more rapidly than any of the width sensitivity parameters for sediment load, channel gradient and bed material size. By mid-Stage 4, the bank material cohesion is more significant with respect to channel widening than any of these parameters, and is second only to the flow discharge in terms of relative dominance on channel width at this time (Figure 5A). This is an indication of the dominance of bank processes over bed processes on channel form during these stages of channel evolution.

As Stage 4 progresses, the supply of sediment from bank failures and upstream bed degradation increases, boundary shear stress is reduced as the channel depth and gradient decrease, deposition begins to occur and the rate of widening diminishes (Schumm *et al.*, 1984; Thorne and Osman, 1988). Eventually, the width stabilizes and bed aggradation occurs due to continued inputs of sediment from widening upstream. This is late Stage 4 and Stage 5 of the channel evolution sequence (Figure 5C). Figure 5A indicates that this sequence of events is reflected in simulated shifts in the relative dominance of the fluvial system variables. For the channel width sensitivity parameters, the 'bed process' variables (channel gradient, sediment load, bed material size) continue to increase or remain constant with time, while the bank material cohesion

width sensitivity parameter decreases after mid-Stage 4. By late Stage 4, the relative dominance of bank material cohesion with respect to width drops back below the sediment load and channel gradient (Figure 5A). The flow discharge continues to be the most dominant and bed material size the least dominant variables during this time, maintaining approximately constant width sensitivity parameters. It is apparent that as the channel widening rate decreases, the bed begins to aggrade and the channel tends towards dynamic equilibrium, and 'bed process' variables increase in significance and reduce the level of the relative dominance of the bank material cohesion, at least with respect to channel width.

The significance of the onset of widening is also evident in the shifting dominance of the depth sensitivity parameters for tested variables after Stage 2 (Figure 5B). After the onset of widening (Stage 3), early in Stage 4, all the 'bed process' variables (sediment load, channel gradient, bed material size), as well as channel discharge, decrease non-linearly with time, all these parameters eventually reaching constant values by late Stage 4 (Figure 5B). The trends of the curves for these parameters during this time are similar, so that the relative dominance of the 'bed process' parameters remains the same as during Stage 2, prior to the onset of widening. After the onset of widening, the depth sensitivity parameter for bank material cohesion rapidly increases by approximately two orders of magnitude, then as widening diminishes during mid- to later Stage 4, the depth sensitivity parameter for bank material cohesion slows and attains a near-constant value by late State 4 (Figure 5B).

The effect of these changes is that by early Stage 4, the significance of bank material cohesion with respect to depth is greater than the significance of bed material size with respect to depth. By mid-Stage 4, the depth sensitivity parameter for bank material cohesion is more significant than the sediment load, and by late Stage 4 the bank material cohesion and channel gradient are approximately equal in terms of their relative dominance with respect to channel depth, behind (by approximately an order of magnitude) flow discharge only (Figure 5B), as noted in the results for stable channels discussed previously.

Stage 5 channels represent the final stage of channel adjustment, the attainment of a new channel morphology in dynamic equilibrium. At this stage of channel adjustment, the sensitivity parameters for both width and depth attain approximately constant but non-zero values, reflecting the overall stability of the system. The values of the sensitivity parameters correspond to the magnitudes of the stable channel sensitivity parameters discussed previously (Figure 4). Thus, for stable channel width, discharge is the dominant variable, followed by the channel gradient and sediment supply, bank material cohesion and size of the bed material. For channel depth, discharge is also the dominant variable, followed by channel gradient, bank material cohesion, sediment supply and bed material size.

The rapid shifts in dominance of parameter sensitivity coincident with initiation of channel widening simulated in this paper indicate how widening damps vertical adjustment (reductions of relative dominance of discharge, sediment load, channel gradient and bed material size with respect to bank cohesion during Stages 3 and 4). This is consistent with the interpretation of the critical bank height as a threshold controlling morphological adjustment (Thorne and Osman, 1988). The threshold acts as a limit on continued degradation and switches the predominant direction of morphological response from the vertical to the lateral. This indicates the significance of channel widening as an integral, and perhaps dominant, mode of channel response. Channel widening is particularly helpful in aiding the recovery of channels destabilized by degradation, since widening provides a supply of bank materials to sediment-starved channels and also reduces flow depth and decreases boundary shear stress, simultaneously reducing sediment transport capacity. For this reason Simon (1992) has argued that channel widening is often the dominant morphological response of unstable channels. One implication of this is that attempts to constrain the width of unstable channels with limited sediment supply for engineering purposes may be counter-productive. In such cases the channel's only means of retaining equilibrium is degradation of the bed, which may undermine structures and dangerously constrict high magnitude floods in deep, narrow channels.

CONCLUSION

In this paper a physically based numerical model of channel evolution was used to establish the sensitivity of channel morphological response to changes in a range of parameters representing flow, sediment and

topographic boundary conditions. The results show that the magnitudes of stable channel depths attained in sand-bed streams with cohesive bank materials following destabilization due to bed degradation and widening are most sensitive to variations in channel discharge. The critical threshold for entrainment of cohesive bank materials appears to be as important as the discharge in controlling stable channel widths. Channel widths and depths are also sensitive to the magnitude of the sediment load, channel gradient, bank material cohesion, and the initial bank height. However, these variables were found to have sensitivity parameters approximately an order of magnitude smaller than the channel discharge. Variations in bed material characteristics within the sand-size range have little impact on simulated stable channel morphology.

The relative importance of tested control variables changes during unstable channel evolution, corresponding to different modes of process dominance as the channel morphology evolves through various stages towards a more stable configuration. A strong process discontinuity is identified at the point at which bed degradation causes the banks to become unstable with respect to mass-failure, initiating a phase of widening. Prior to this stage, channel response is most sensitive to the variables which control bed processes. After this stage, during the rapid widening phase, channel response (both width *and* depth adjustment) is primarily sensitive to variables which control bank processes. This result, obtained from application of a physically based numerical model, supports the idea proposed by Thorne and Osman (1988), based on an empirical-conceptual model, that the critical bank height required to initiate mass-failure represents a significant geomorphic threshold. Crossing the threshold leads to abrupt changes in the morphological response of the channel.

The results obtained in this study have some practical utility in identifying those variables which, if not correctly specified or predicted in a modelling study, may result in significant errors in simulated response. Alternatively, the results may be used to identify those variables for which changes in values as a result of environmental change might lead to significant morphological response. The results suggest that the discharge and sediment load independent variables must be specified accurately if the response of a channel is to have any chance of being simulated correctly using the Darby–Thorne numerical model. Values of discharge and sediment load are known to be susceptible to climate and land-use changes. The relatively high sensitivity parameters, especially for discharge, are consistent with the findings of large numbers of studies which have emphasized the influence of environmental change on channel adjustment. Finally, simulations were also found to be highly sensitive to the critical entrainment threshold for cohesive bank materials, a parameter for which no reliable method of prediction yet exists. Research into this topic is, therefore, urgently required to improve the predictive ability and utility of simulation models such as that applied here.

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